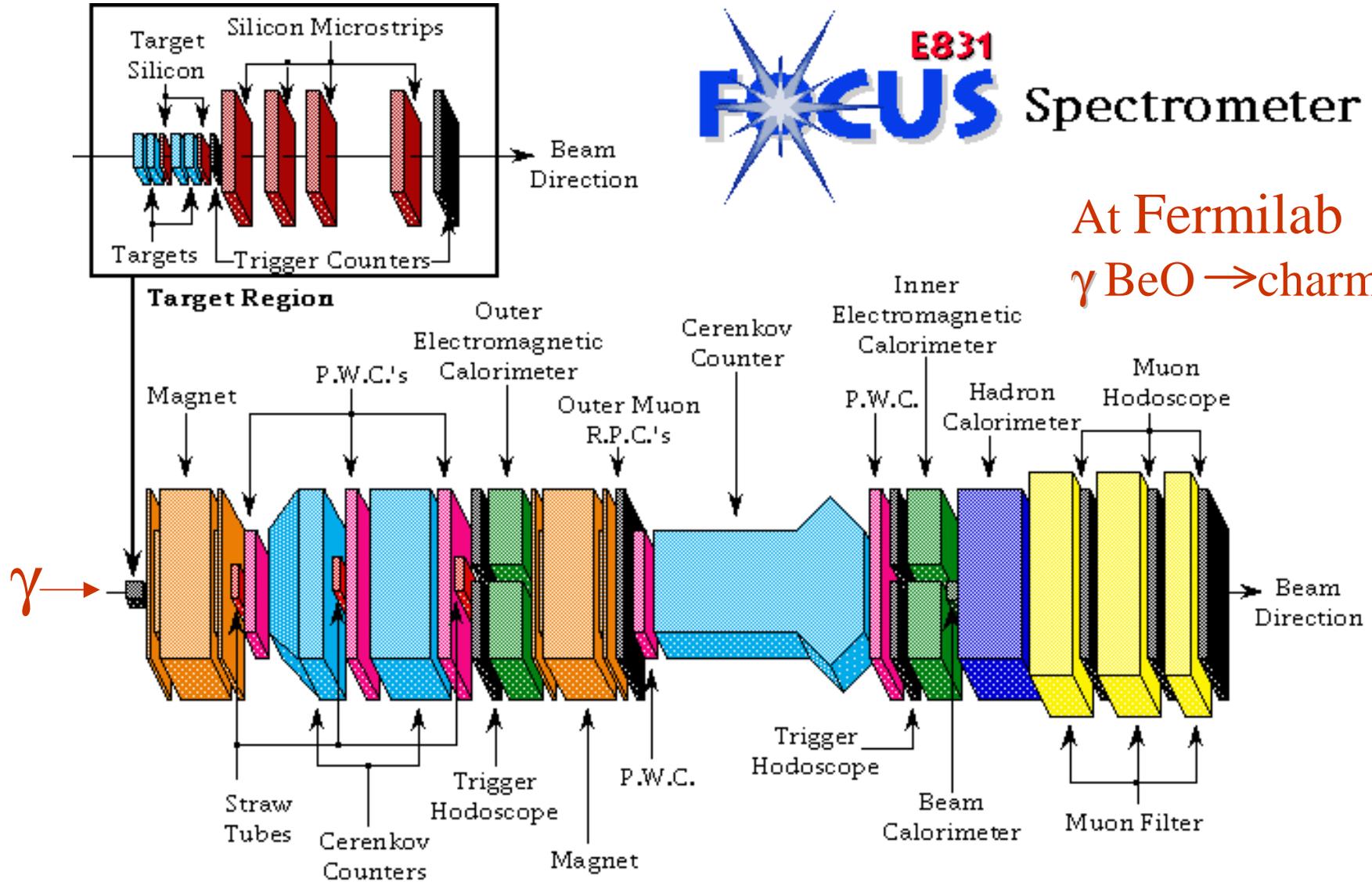


# Charmed Hadron Spectroscopy At



Robert K. Kutschke  
Fermilab  
HQ2K October 11, 2000

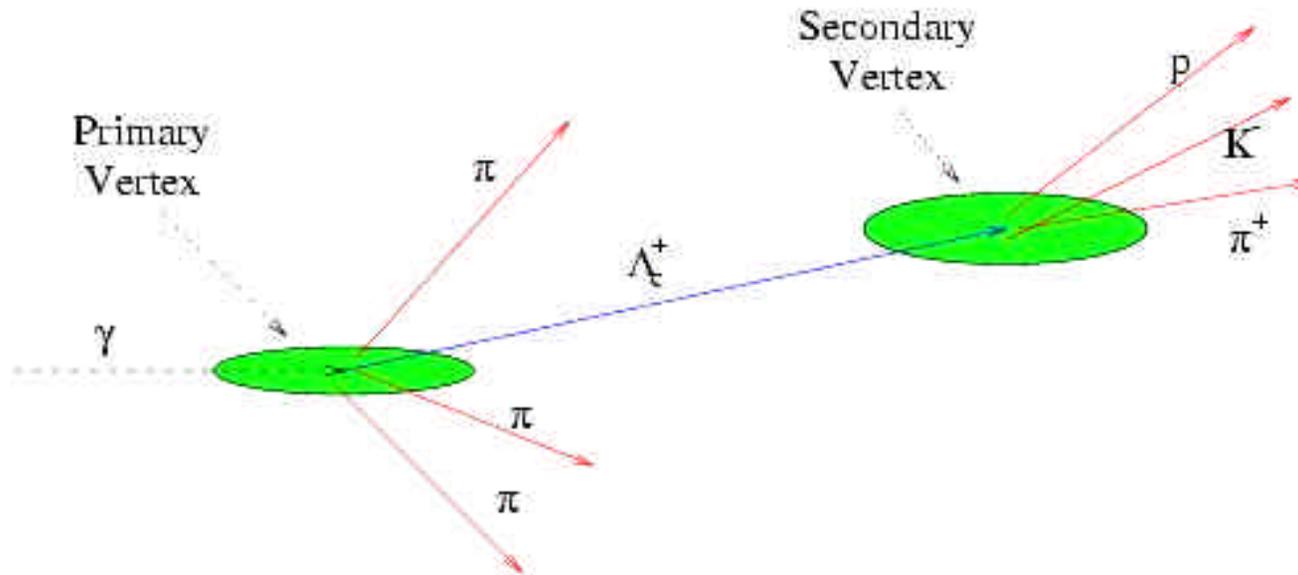
1. Introduction
2.  $\Sigma_C$ ,  $\Sigma_C^*$
3.  $\Lambda_C^*$
4.  $D^{**}$
5.  $D_S^{**}$ .



## FOCUS: The Successor to E687

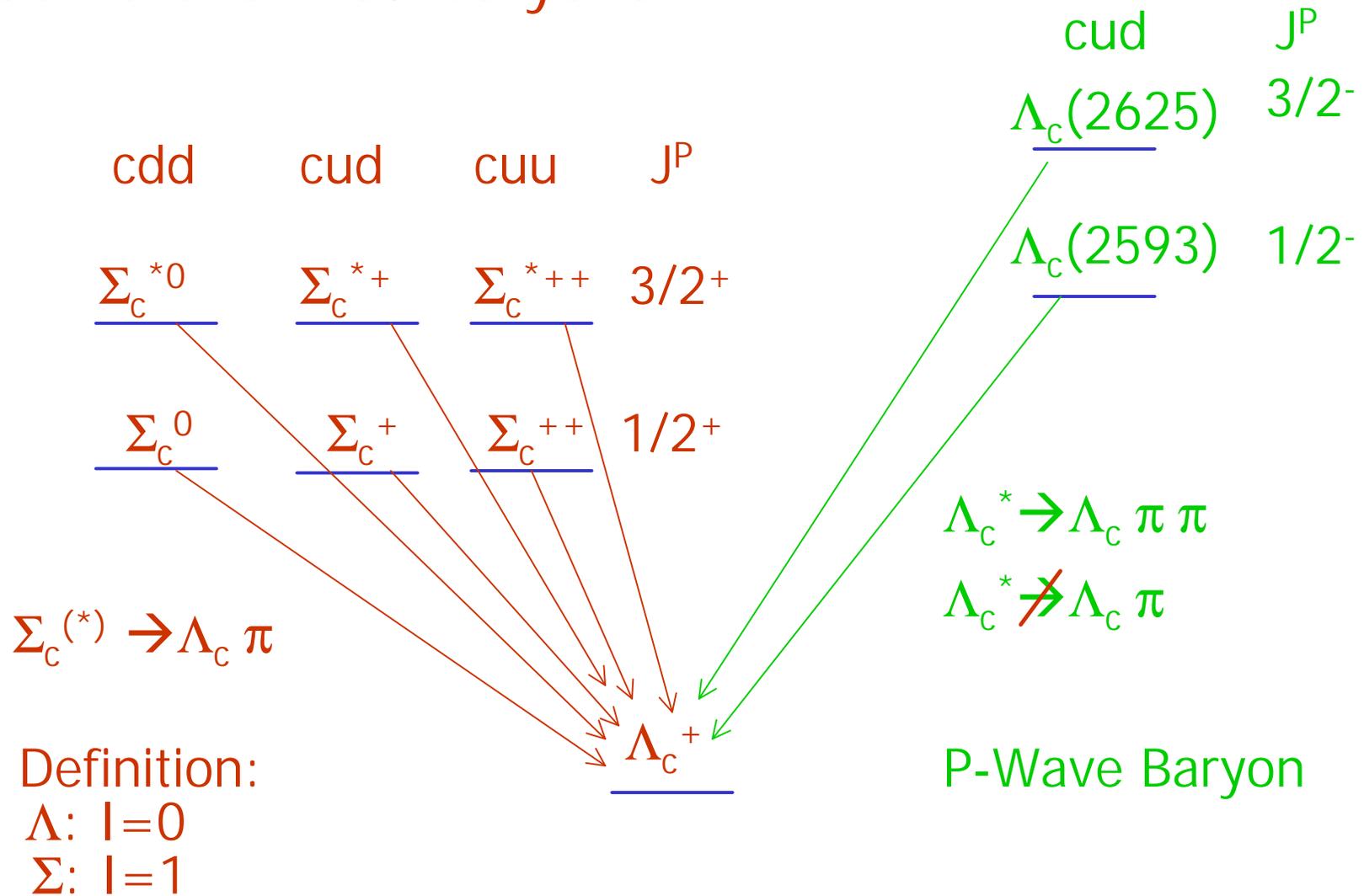
- Segmented BeO Target interleaved with SMDs.
- Upgraded:
  - EM Calorimetry.
  - Cerenkov system.
  - Muon ID capability.
- Data taken in 1996-1997.
- More than 10 times the Luminosity
  - $>10^6$  reconstructed “Golden Mode” Decays:  
 $D^0 \rightarrow K^- \pi^+$ ,  $K^- \pi^+ \pi^- \pi^+$  and  $D^+ \rightarrow K^- \pi^+ \pi^+$ .

# Candidate Driven Vertexing

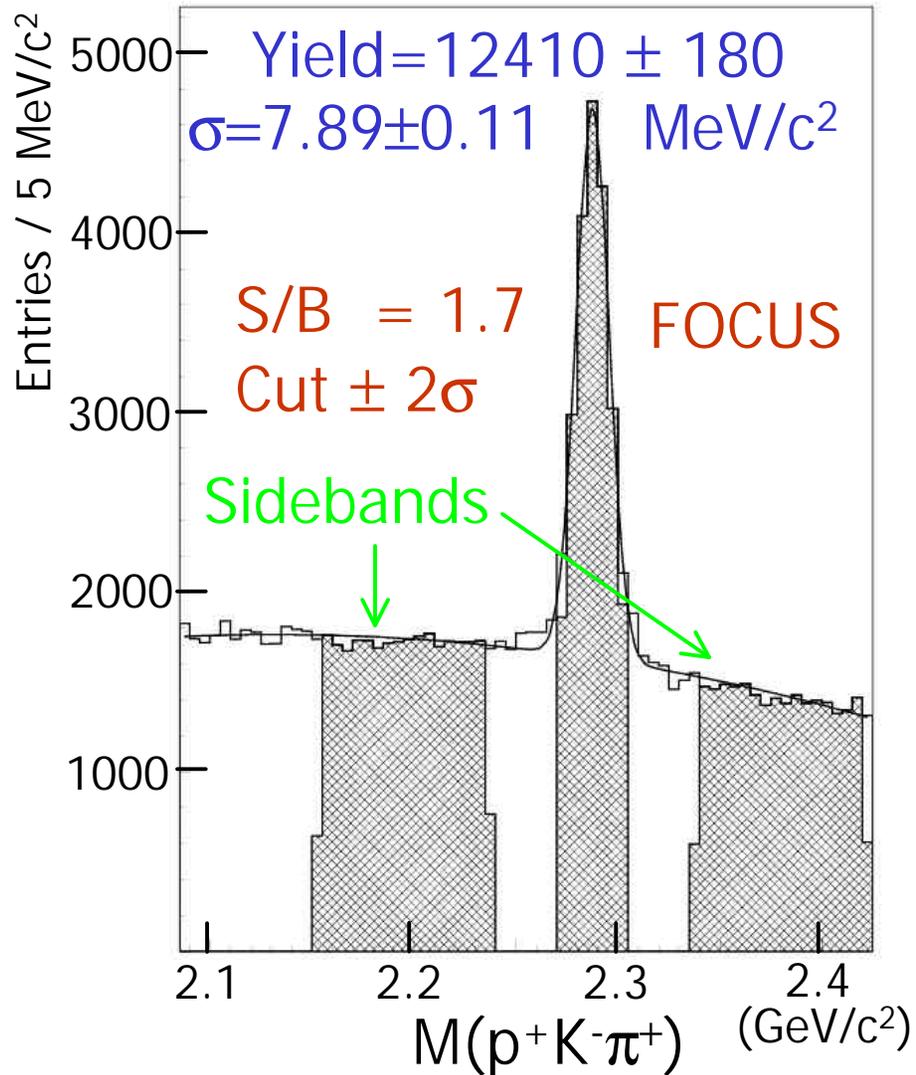


- Find charm candidate: good vertex, good particle ID.
- Seed primary vertex finder with the charm candidate.
- Require isolated secondary. One measure:  $L/\sigma_L > \text{cut}$ .
- Add tracks from primary to form  $\Lambda_c \pi$  combinations.

# Some Charmed Baryons:

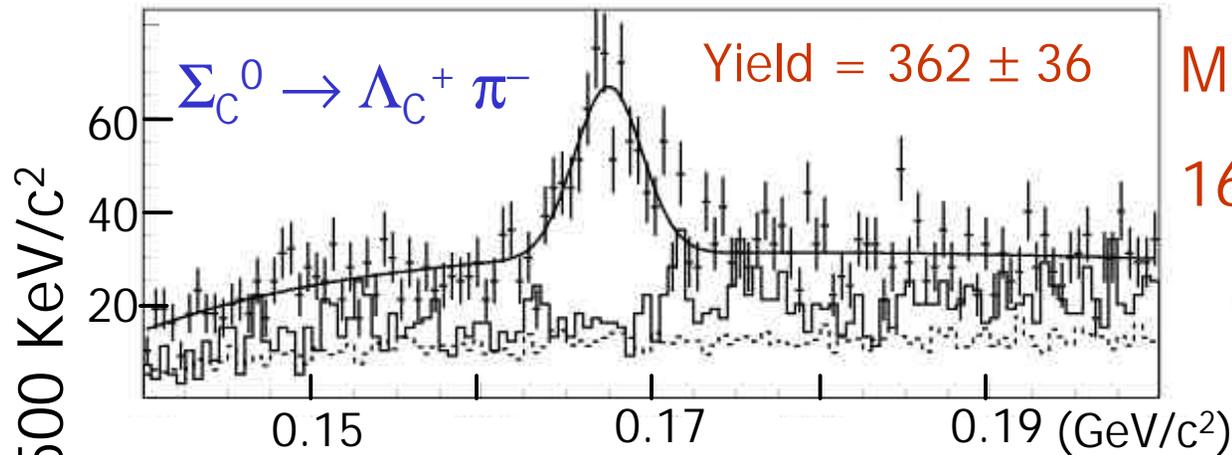


## Selection of $\Lambda_c$ for $\Sigma_c^{++}$ and $\Sigma_c^0$ Studies



- $L/\sigma_L > 6$ .
- Isolated secondary vertex.
- C affirmative Id for p and K
- C consistency for  $\pi$
- For  $\Sigma_c^+$  study
  - $L/\sigma > 4$ , Looser C.
  - Yield =  $18346 \pm 248$
  - S/B = 1.19

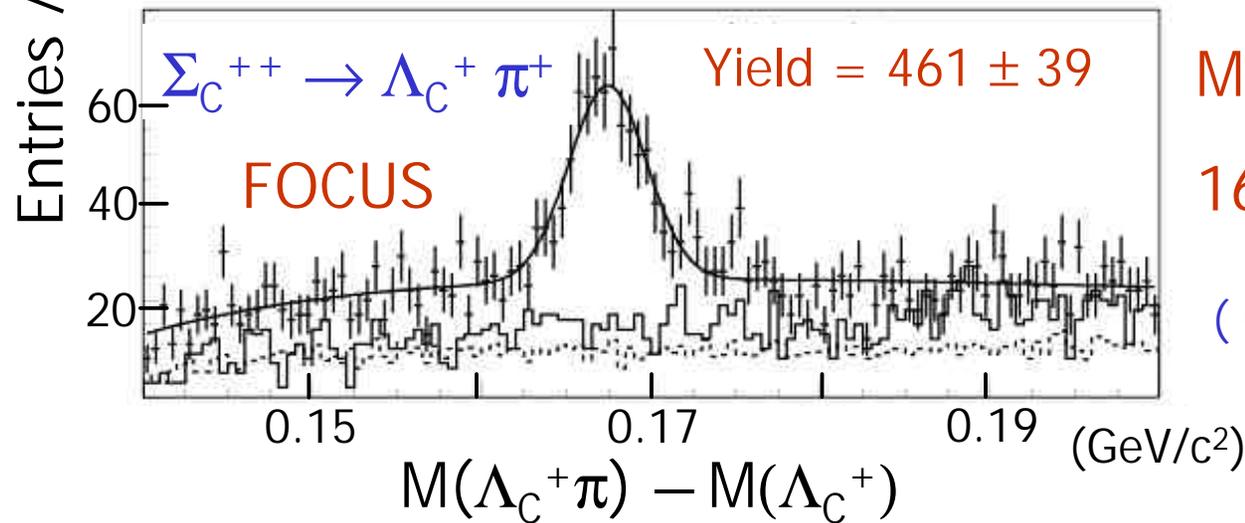
# $\Sigma_c^{++}$ and $\Sigma_c^0$ Masses



$$M(\Sigma_c^0) - M(\Lambda_c^+) =$$

$$167.38 \pm 0.21 \text{ MeV}/c^2$$

(CLEO 2.5 ICHEP 2000  
 $167.2 \pm 0.1 \pm 0.2 \text{ MeV}/c^2$ )



$$M(\Sigma_c^{++}) - M(\Lambda_c^+) =$$

$$167.35 \pm 0.19 \text{ MeV}/c^2$$

(CLEO 2.5 ICHEP 2000  
 $167.4 \pm 0.1 \pm 0.2 \text{ MeV}/c^2$ )

## Systematic Errors

Source	Systematic Error (MeV/c <sup>2</sup> )		
	$\Sigma_c^{++} - \Lambda_c^+$	$\Sigma_c^0 - \Lambda_c^+$	$\Sigma_c^{++} - \Sigma_c^0$
Momentum Scale	0.05	0.05	0.00
Fitting	0.02	0.06	0.04
Recon. Bias	0.04	0.04	0.00
Analysis Cuts	0.10	0.10	0.10
Total	0.12	0.13	0.11

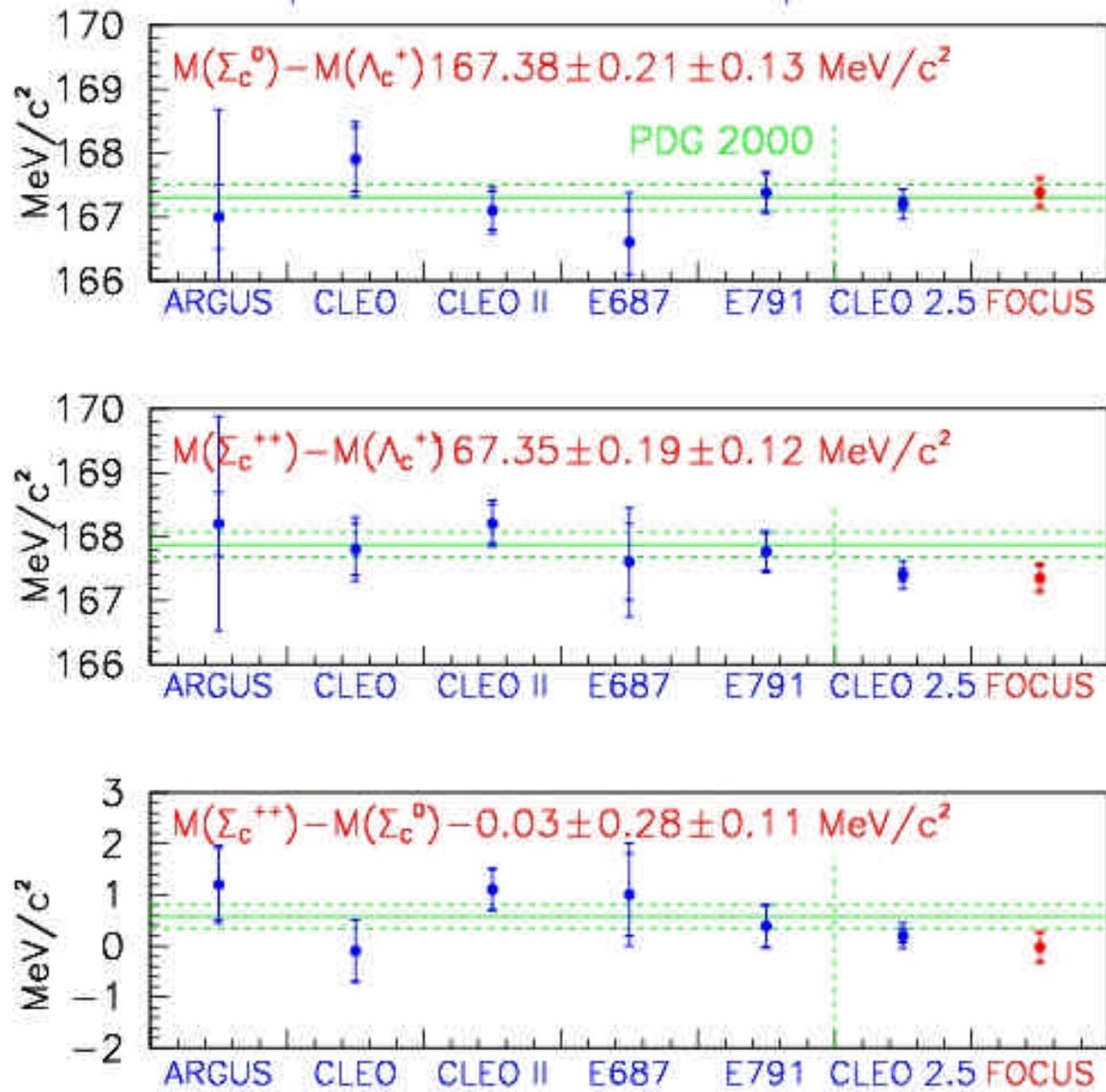
$$M(\Sigma_c^0) - M(\Lambda_c^+) = 167.38 \pm 0.21 \pm 0.13 \text{ MeV}/c^2$$

$$M(\Sigma_c^-) - M(\Lambda_c^-) = 167.35 \pm 0.19 \pm 0.12 \text{ MeV}/c^2$$

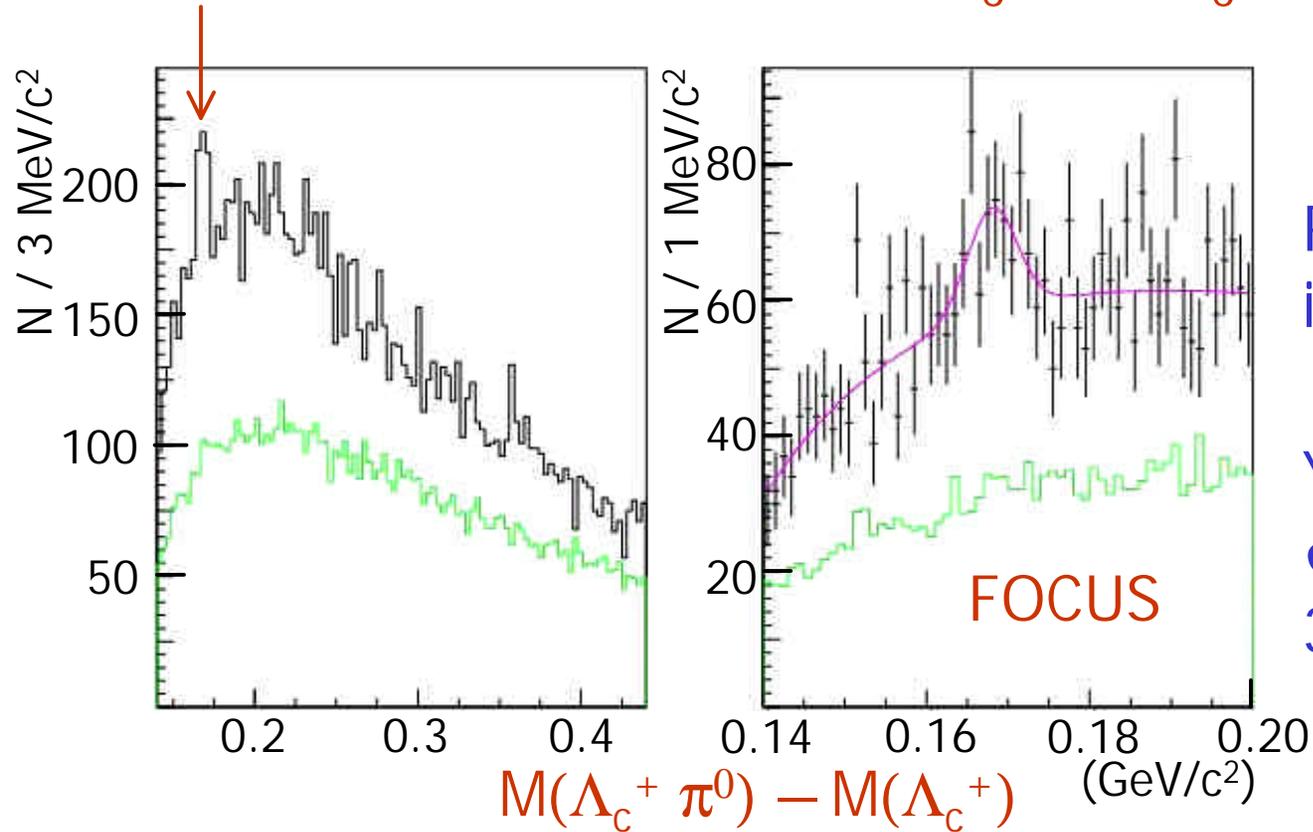
$$M(\Sigma_c^{++}) - M(\Sigma_c^0) = -0.03 \pm 0.28 \pm 0.11 \text{ MeV}/c^2$$

Phys. Lett. B488, 218-224, 2000.

### Comparison with Other Experiments



# Observation of $\Sigma_c^+ \rightarrow \Lambda_c^+ \pi^0$



$\pi^0 \rightarrow \gamma\gamma$   
Reconstructed  
in EMCAL.

Yield =  $118 \pm 40$   
 $\sigma =$   
 $3.04 \pm 0.84 \text{ MeV}/c^2$

Preliminary

$$M(\Sigma_c^+) - M(\Lambda_c^+) = 168.0 \pm 1.0 \pm 0.3 \text{ MeV}/c^2$$

$$M(\Sigma_c^+) - M(\Sigma_c^0) = 0.6 \pm 1.0 \pm 0.3 \text{ MeV}/c^2$$

(CLEO hep\_ex/0007041:  $M(\Sigma_c^+) - M(\Lambda_c^+) = 166.4 \pm 0.2 \pm 0.3 \text{ MeV}/c^2$ )

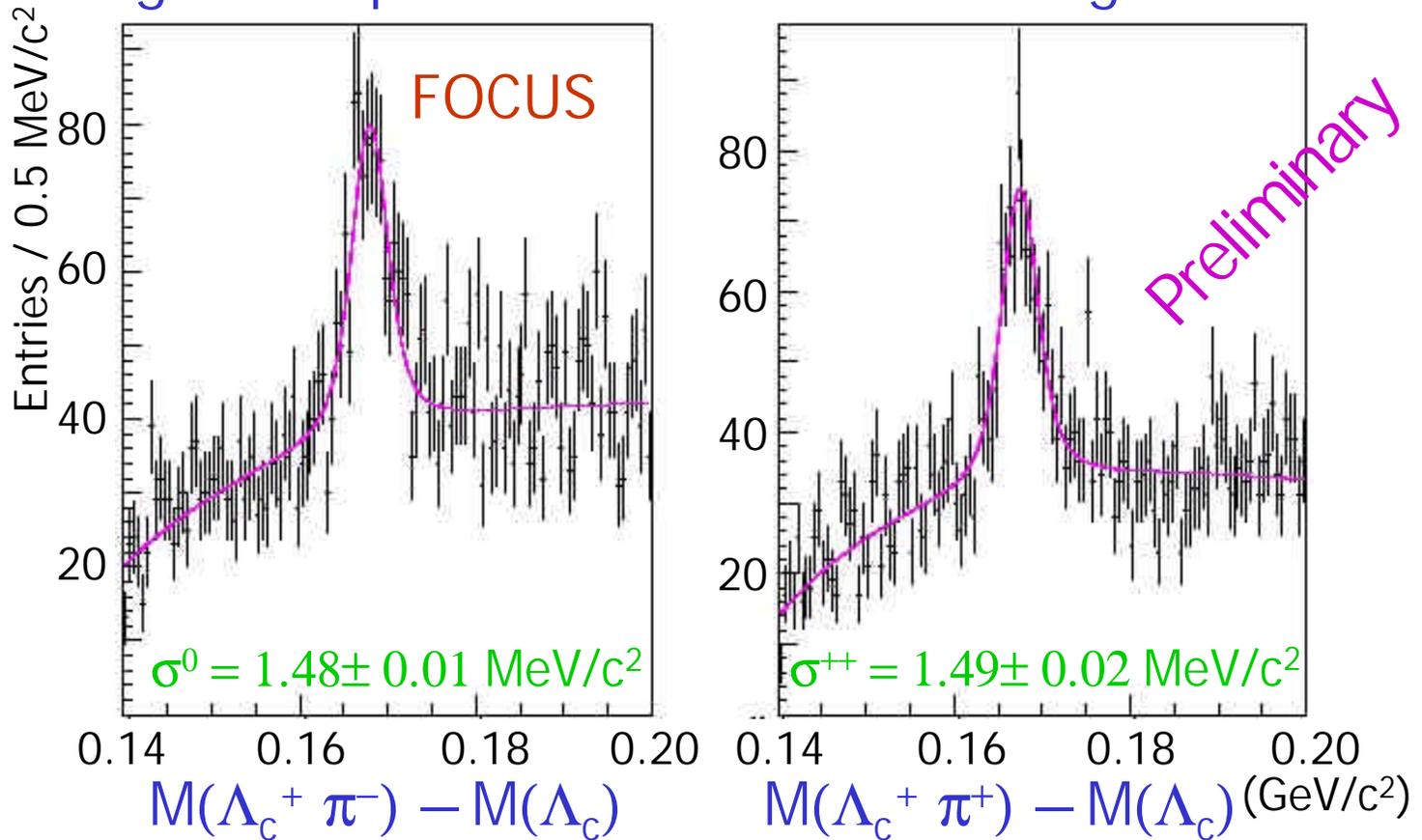
## Isospin Mass Differences

Particles	Mass Difference (MeV/c <sup>2</sup> )		
	PDG 1998	CLEO 2.5	FOCUS
N-P	1.293318 ± 0.000009		
$\Delta^0 - \Delta^{++}$	2.6 ± 0.4		Preliminary
$\Sigma^- - \Sigma^+$	8.08 ± 0.08		
$\Xi^- - \Xi^0$	6.4 ± 0.6		
$\Xi_c^0 - \Xi_c^+$	4.7 ± 0.6		
$\Sigma_c^0 - \Sigma_c^{++}$	-0.57 ± 0.23		0.03 ± 0.28 ± 0.11
$\Sigma_c^0 - \Sigma_c^+$	-1.4 ± 0.6	0.7 ± 0.5	-0.6 ± 1.0 ± 0.3

Theory has canceling contributions: quark masses, strong potential, Coulomb interaction, hyperfine ( EM + QCD ).

# Natural Widths (MeV/c<sup>2</sup>)

Signal Shape: BW convoluted with a gaussian.



$$\Gamma(\Sigma_c^0) = 2.58 \pm 0.79^{+0.51}_{-0.55}$$

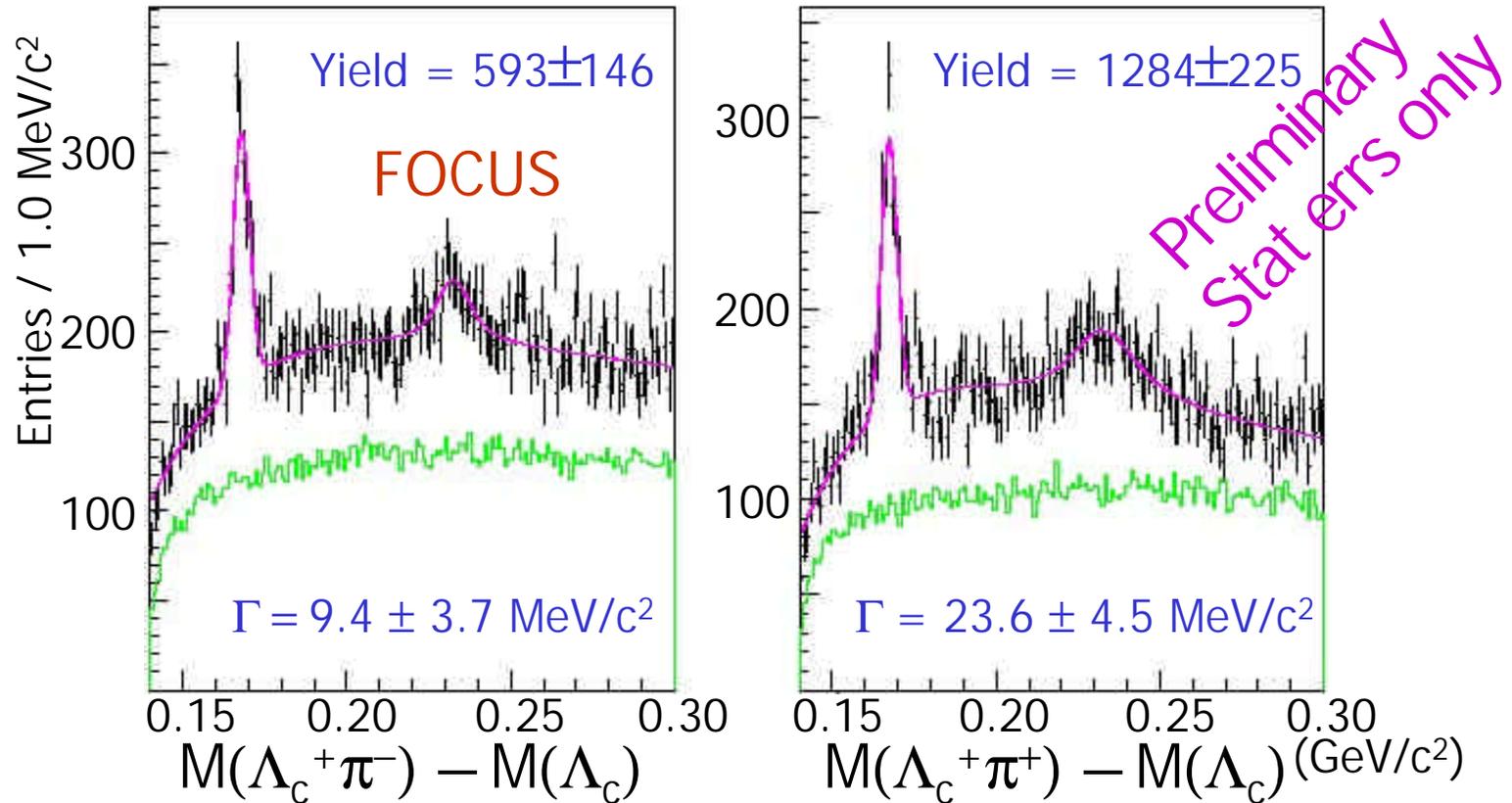
$$\Gamma(\Sigma_c^{++}) = 2.53 \pm 0.77^{+0.51}_{-0.56}$$

( CLEO 2.5 ICHEP 2000:  $\Gamma^0 = 2.4 \pm 0.2 \pm 0.4$      $\Gamma^{++} = 2.5 \pm 0.2 \pm 0.4$  MeV/c<sup>2</sup> )

## $\Gamma(\Sigma_c^{++})$ and $\Gamma(\Sigma_c^0)$

Theoretical Predictions		
Author ‡	$\Gamma$ (MeV/c <sup>2</sup> )	
	$\Sigma_c^0$	$\Sigma_c^{++}$
Ivanov	$2.65 \pm 0.19$	$2.85 \pm 0.19$
Tawfig	1.57	1.64
Huang	2.4	2.5
Pirjol	1.0 - 3.0	1.1 - 3.1
Rosner	$1.32 \pm 0.04$	$1.32 \pm 0.04$
‡ References at end of talk.		
Focus Preliminary Results		
	$2.58 \pm 0.79^{+0.51}_{-0.55}$	$2.53 \pm 0.77^{+0.51}_{-0.56}$

## Observation of $\Sigma_c^{*++}$ and $\Sigma_c^{*0}$

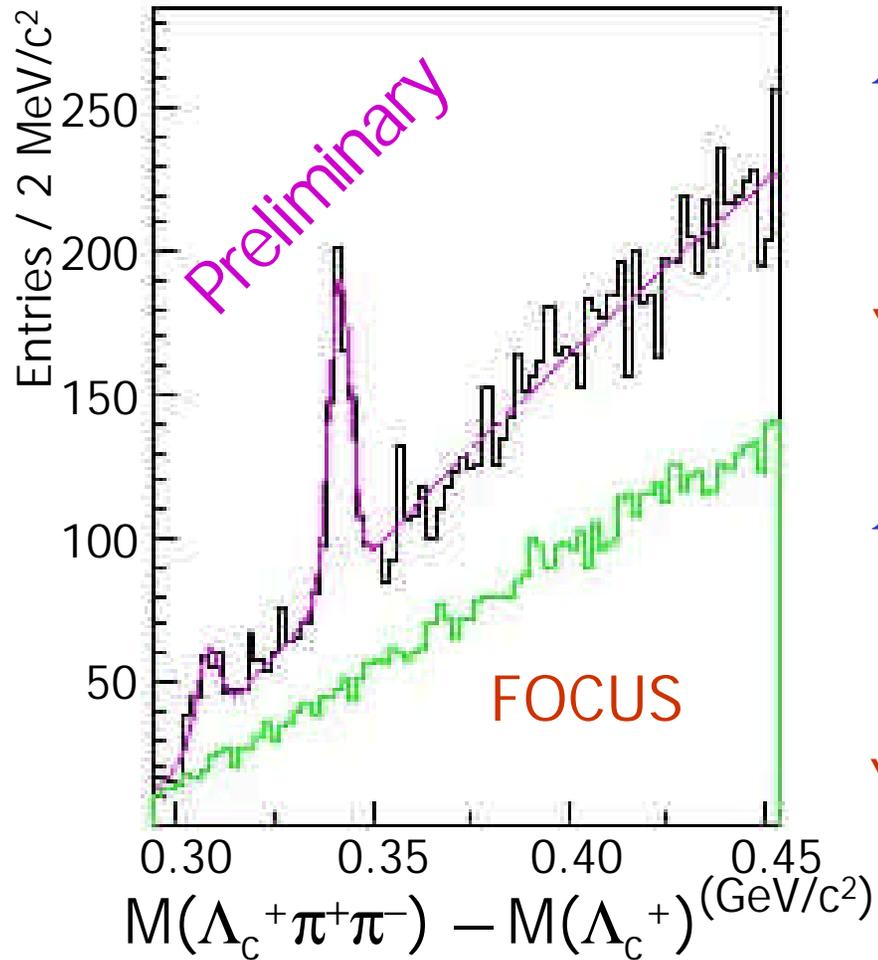


$$\Delta M(\Sigma_c^0) = 232.7 \pm 1.2 \text{ MeV}/c^2 \quad \Delta M(\Sigma_c^{*++}) = 234.2 \pm 1.5 \text{ MeV}/c^2$$

$$M(\Sigma_c^{*0}) - M(\Sigma_c^{*++}) = -1.5 \pm 1.9 \text{ MeV}/c^2$$

(CLEO II:  $\Delta M^0 = 232.6 \pm 1.0 \pm 0.8$   $\Gamma^0 = 13.0 \pm 3.7 \pm 4.0$   $\Delta M^{*++} = 234.5 \pm 1.1 \pm 0.8$   $\Gamma^{*++} = 17.9 \pm 3.8 \pm 4.0$ )

# Observation of Excited $\Lambda_c$ States



$\Lambda_c(2625)$ :

$$\Delta M = 341.6 \pm 0.3 \text{ MeV}/c^2$$

( PDG 2000:  $341.7 \pm 0.6$  )

$$\text{Yield} = 371 \pm 32$$

$\Lambda_c(2593)$ :

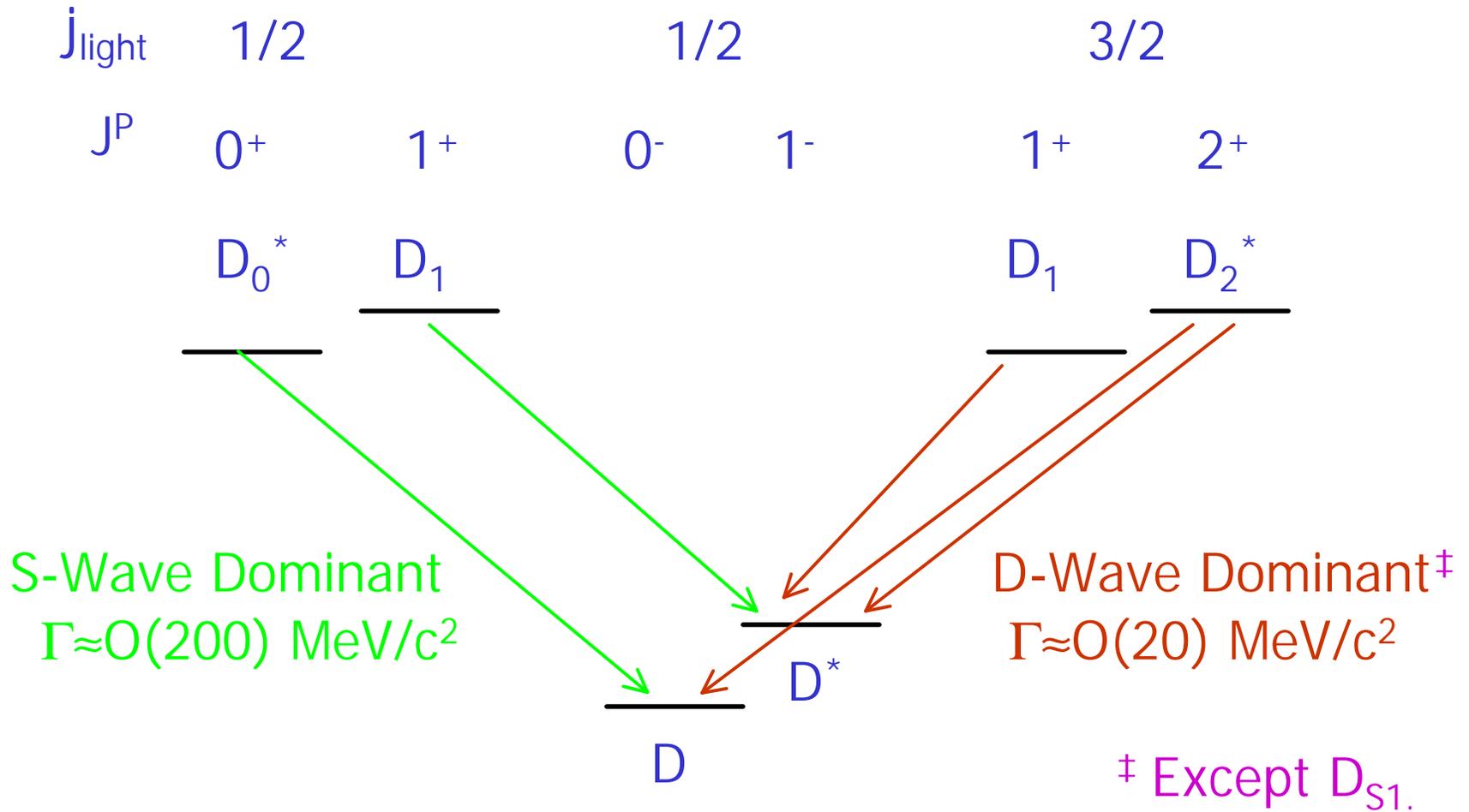
$$\Delta M = 308.1 \pm 0.7 \text{ MeV}/c^2$$

( PDG 2000:  $308.9 \pm 0.6$  )

$$\text{Yield} = 100 \pm 20$$

Errors are Stat only.

# P-Wave Charmed Mesons



## P-Wave Charmed Mesons

- $L=1$  between  $c$  and  $q$ .
- For each of  $cd$ ,  $cu$ ,  $cs$ , expect two doublets:

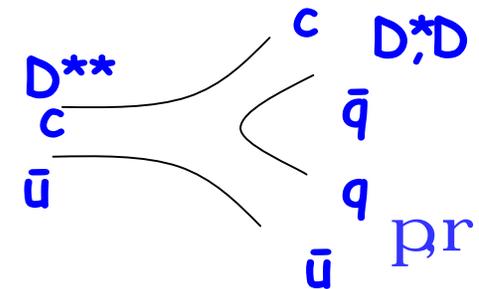
Narrow doublet:

- $\Gamma \approx O(10 \text{ MeV})$
- All observed
- $J^P = (2^+, 1^+)$
- $j_{\text{light}} = 3/2$
- $D^{(*)}\pi$  decay: D wave.

Broad doublet:

- $\Gamma \approx O(100 \text{ MeV})$
- One candidate
- $J^P = (1^+, 0^+)$
- $j_{\text{light}} = 1/2$
- $D^{(*)}\pi$  decay: S wave.

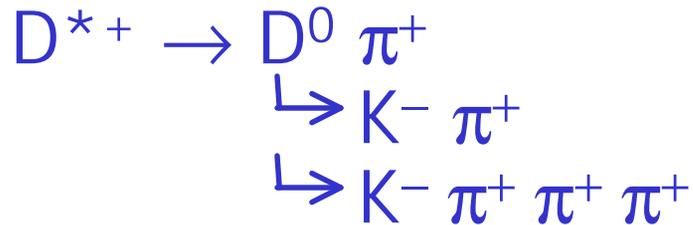
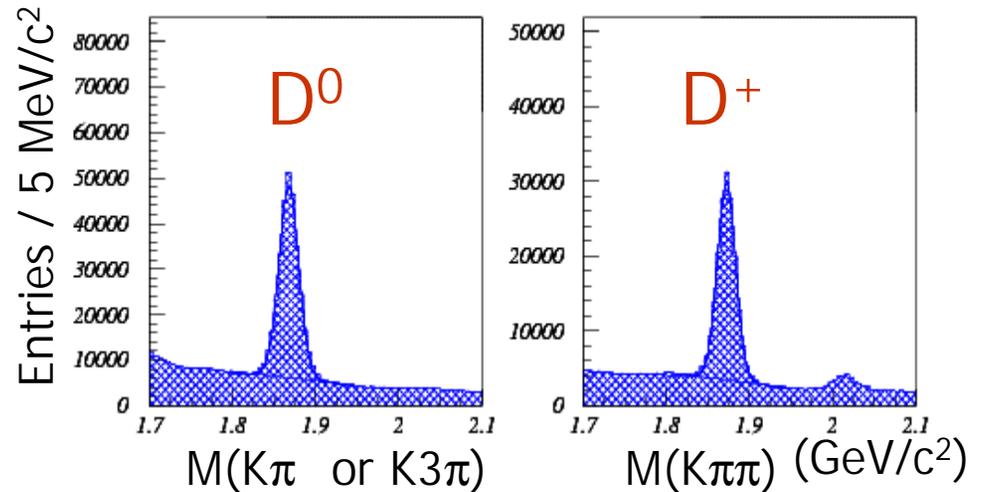
- $j_{\text{light}} = S_{\text{light}} + L$ , a good Q number if  $m_c \gg \Lambda_{\text{QCD}}$
- Dominant decays:  $D\pi$ ,  $D^*\pi$  ( $DK$ ,  $D^*K$  for  $cs$ ).
- Masses within  $\approx \pm 50 \text{ MeV}$  of the multiplet center.



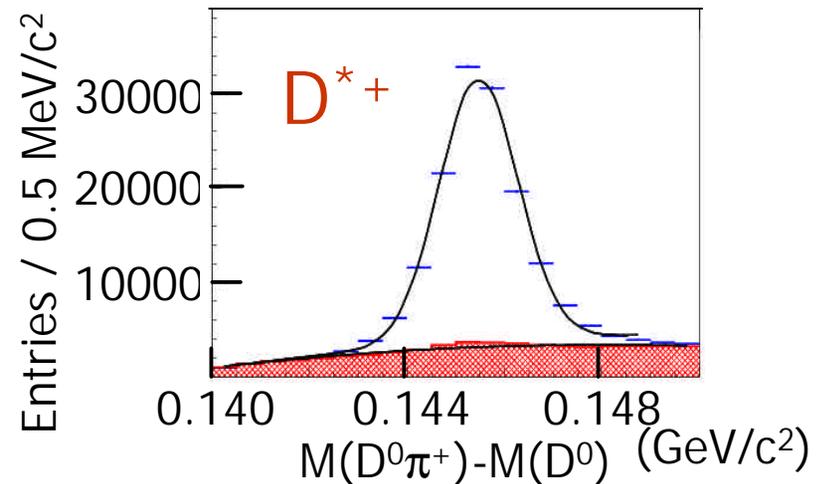
# S-Wave Charm States at FOCUS



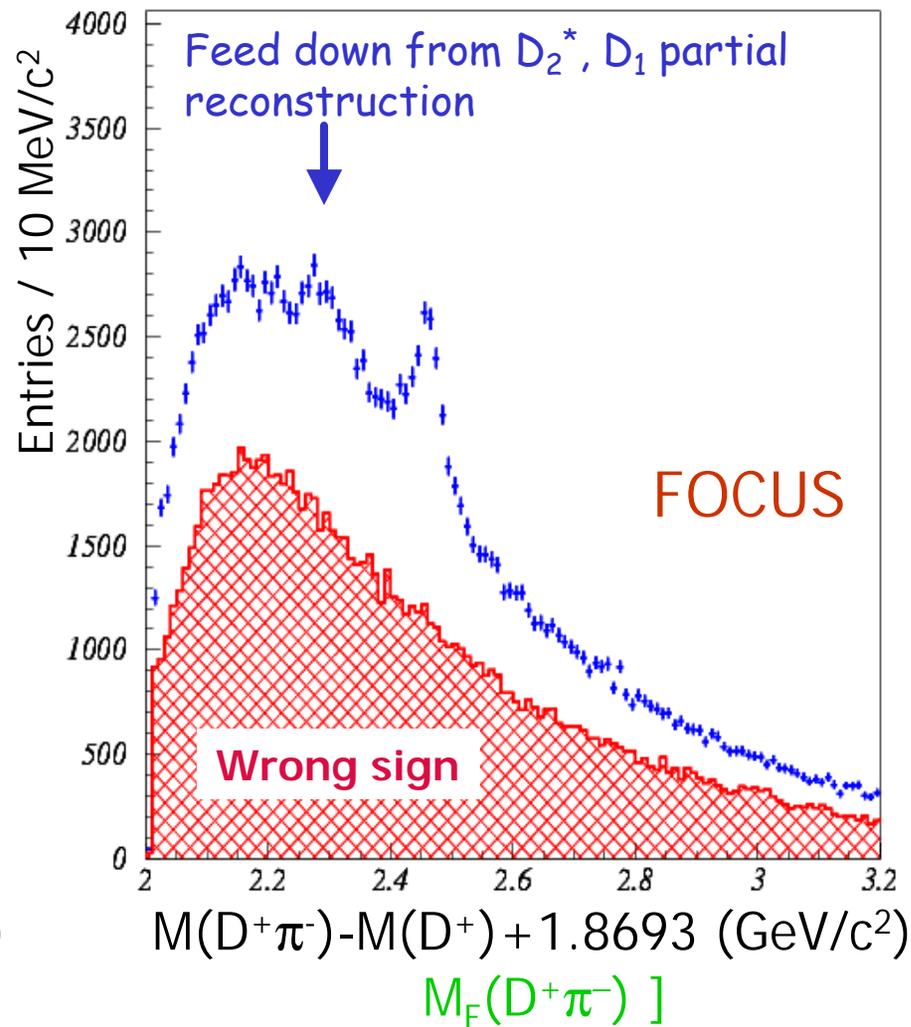
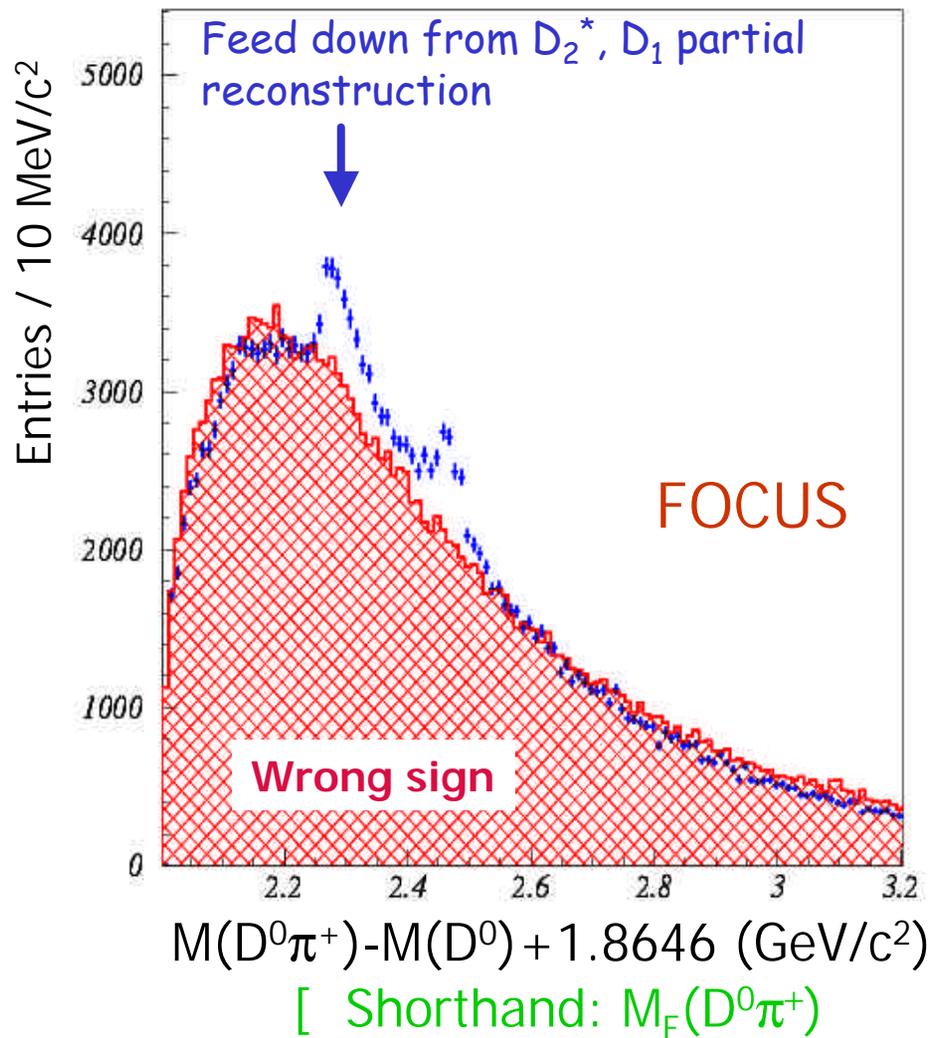
For  $S/B > 7$ ,  
 $> 330,000$  D candidates



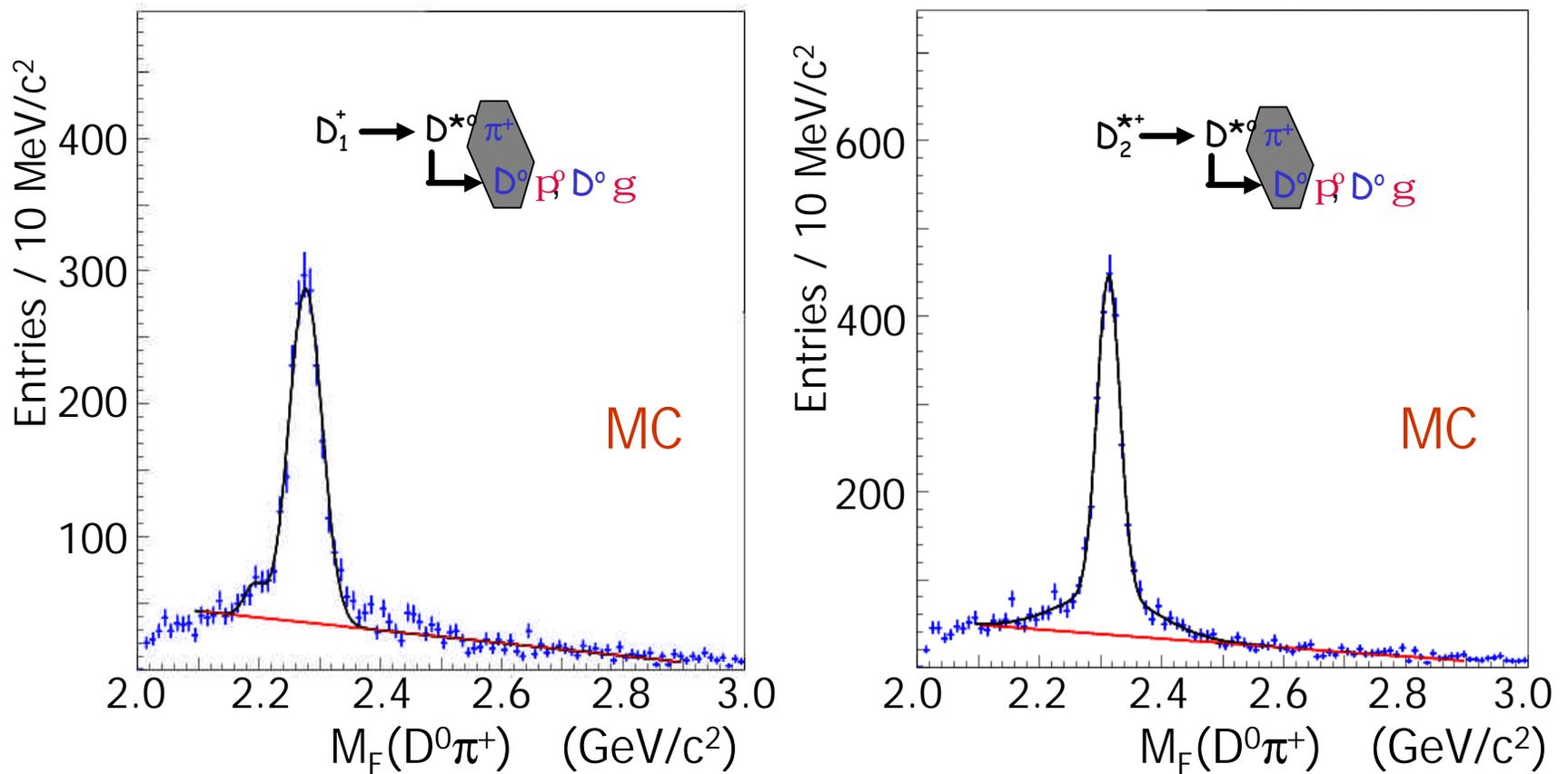
For  $S/B > 5$ ,  
 $\approx 70,000$   $D^{*+}$  candidates



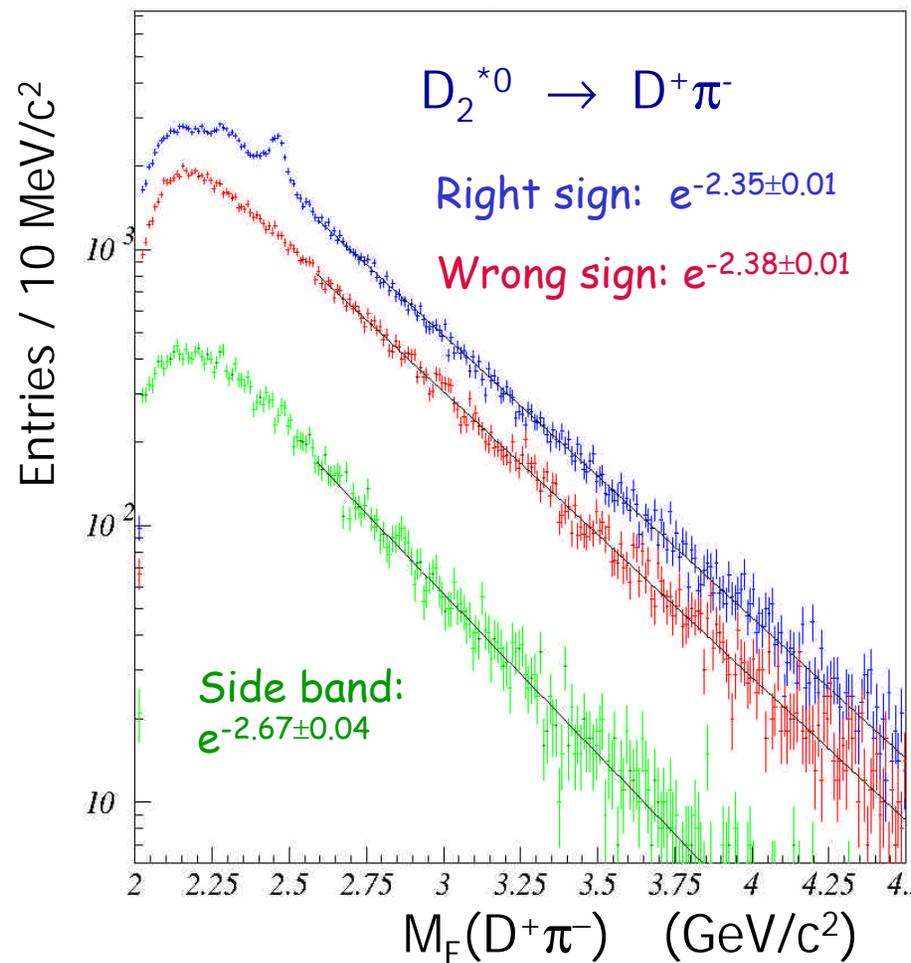
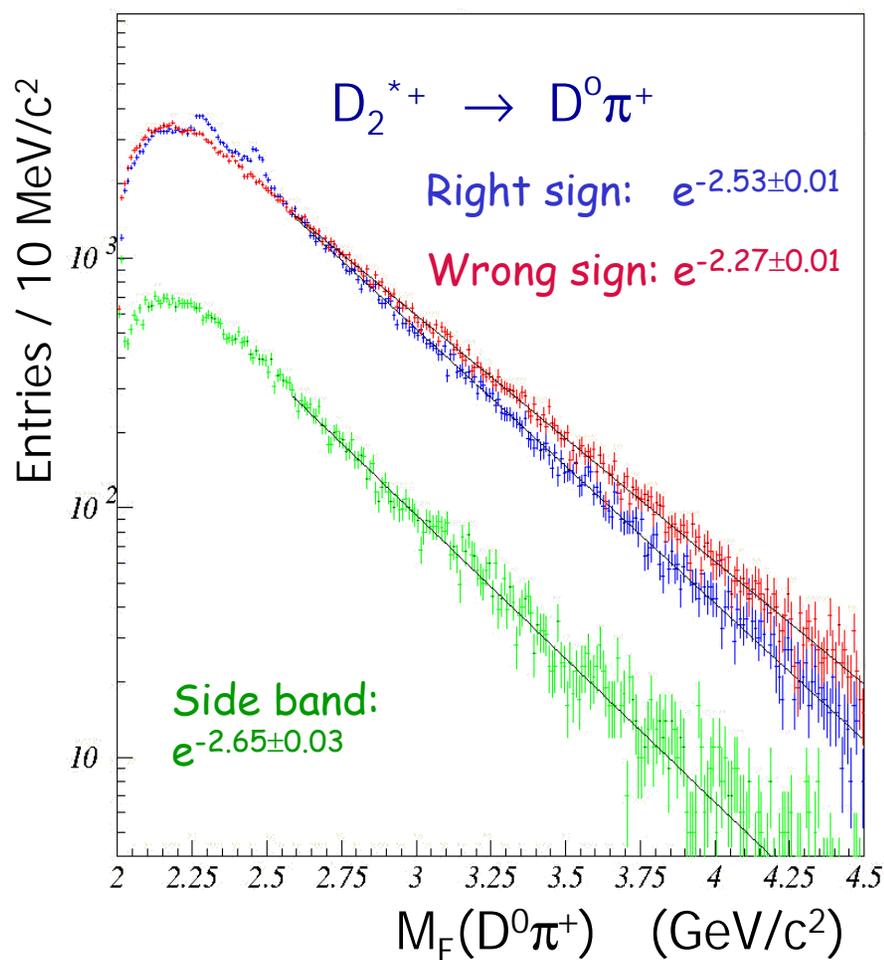
# $D^0\pi^+$ and $D^+\pi^-$ Mass Distributions



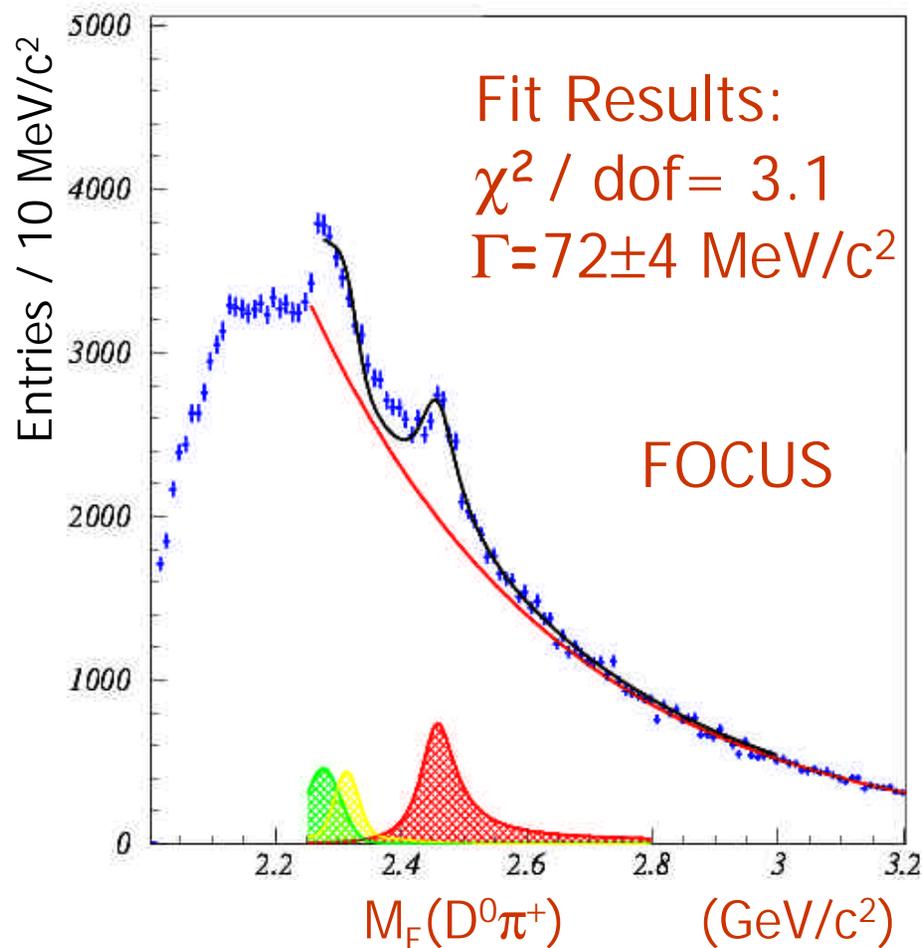
# Get Feed-down Line Shapes from Monte Carlo



# Beyond Signal Region all Shapes are Exponential



# Fitting the $D^0\pi^+$ Mass Distribution (1)



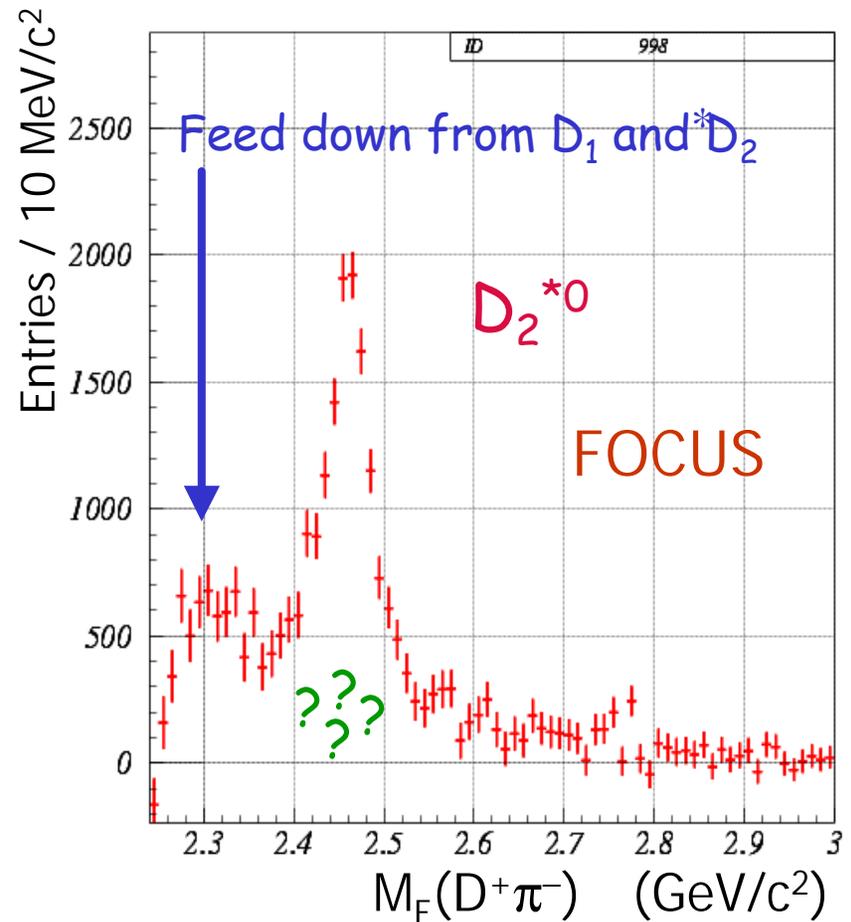
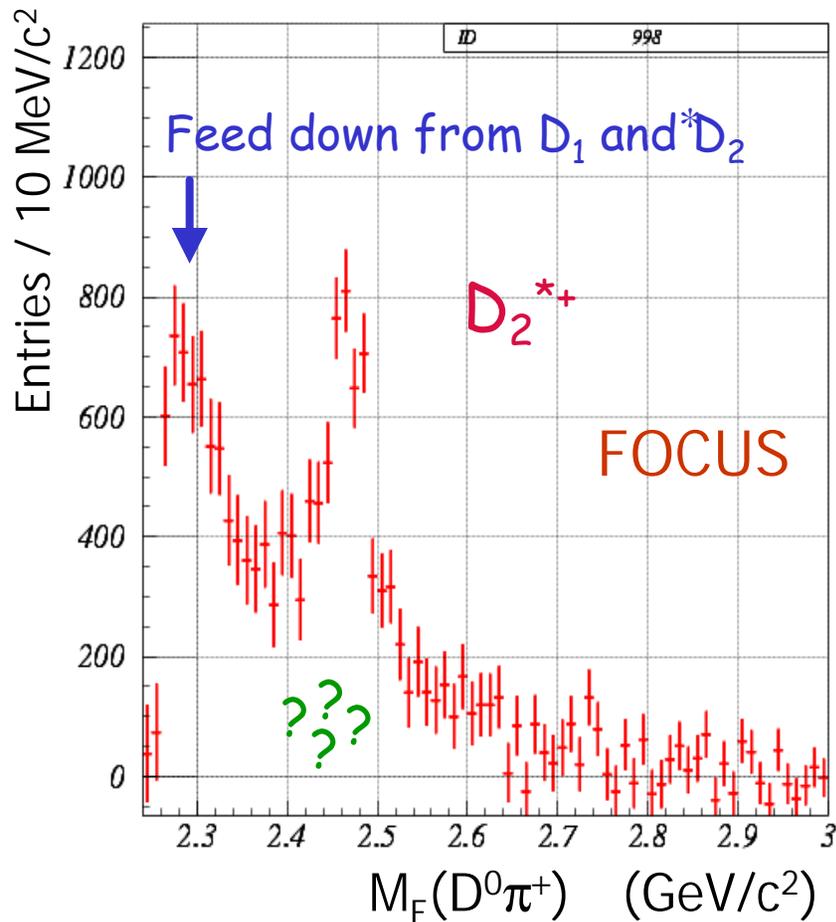
## Terms in the Fit:

1. Signal: D-wave Rel. BW, convoluted with a gaussian,  $\sigma = 7 \text{ MeV}/c^2$ .
2. Exponential extrapolated from 2.4 – 4.5 GeV/c<sup>2</sup>.
3. MC  $D_1$  Feed-down.
4. MC  $D_2$  Feed-down

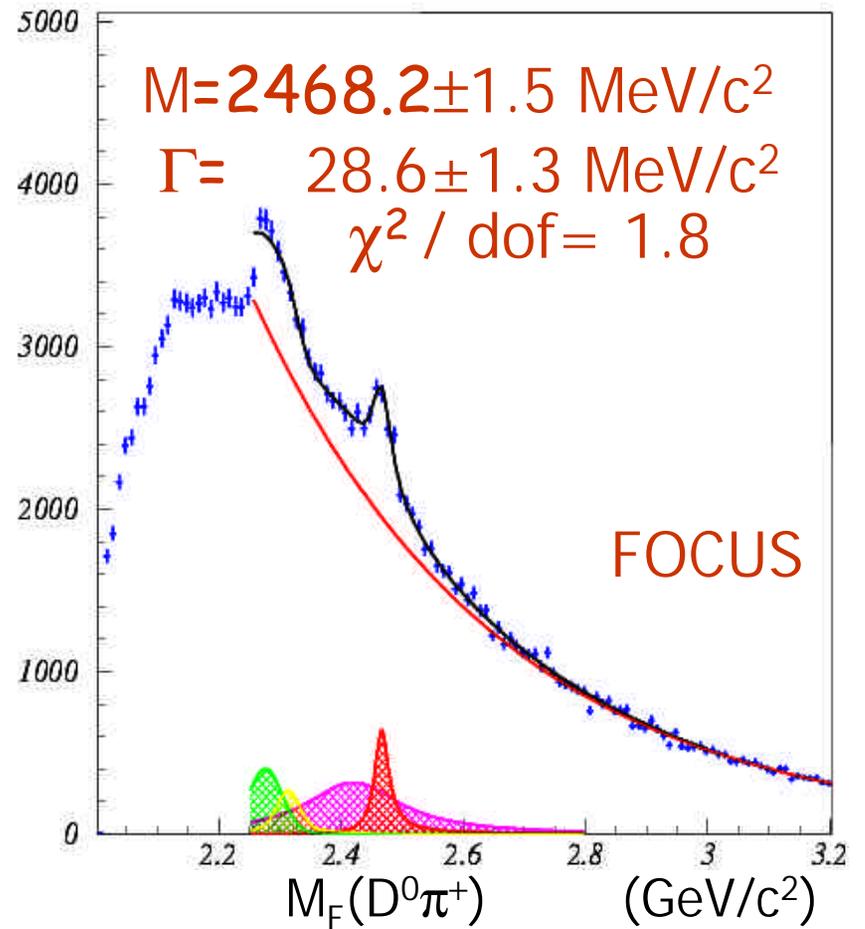
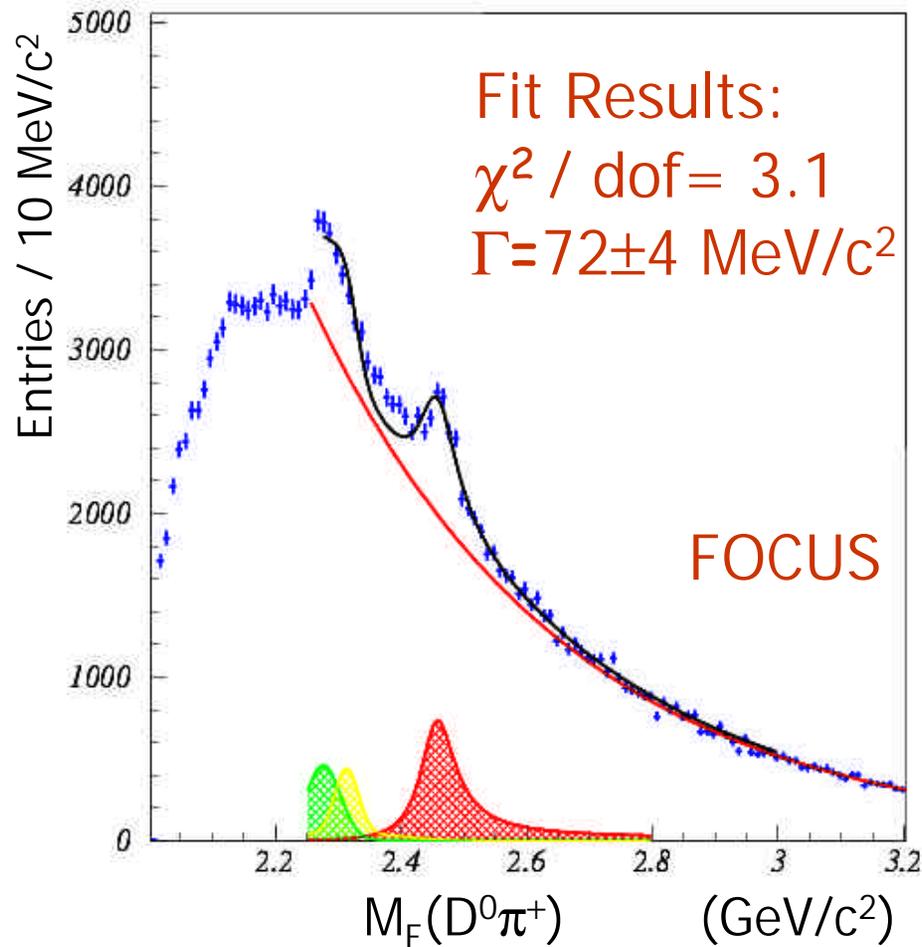
Get horrible fit!

$$(\Gamma_{\text{PDG}}(D_2^{*+}) = 25 \pm 8 \text{ MeV}/c^2)$$

# $D_2^* \rightarrow D\pi$ Exponential Background Subtracted

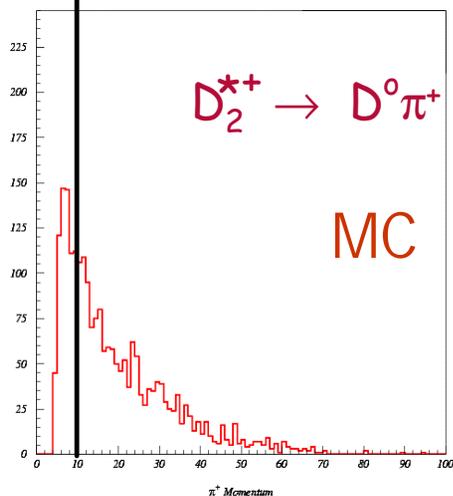
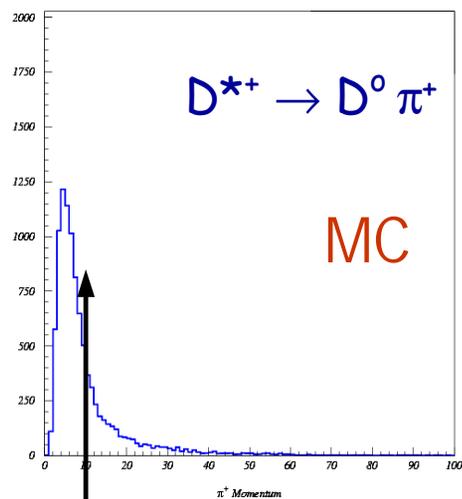


## Fitting the $D^0\pi^+$ Mass Distribution (2)



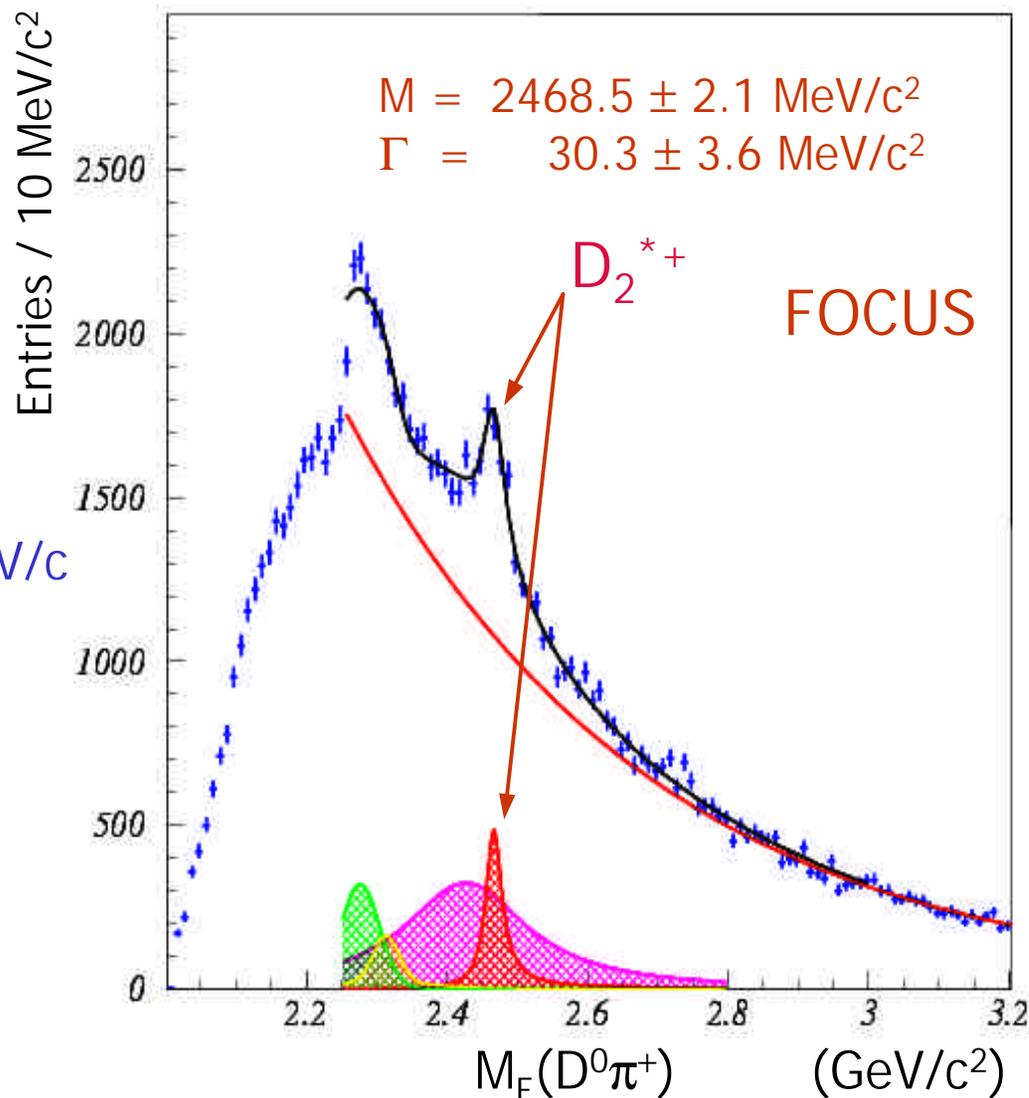
Add 5<sup>th</sup> term to the fit: S-wave Rel. BW

# Reducing BG from Soft $\pi^+$ From $D^{*+}$ Decays

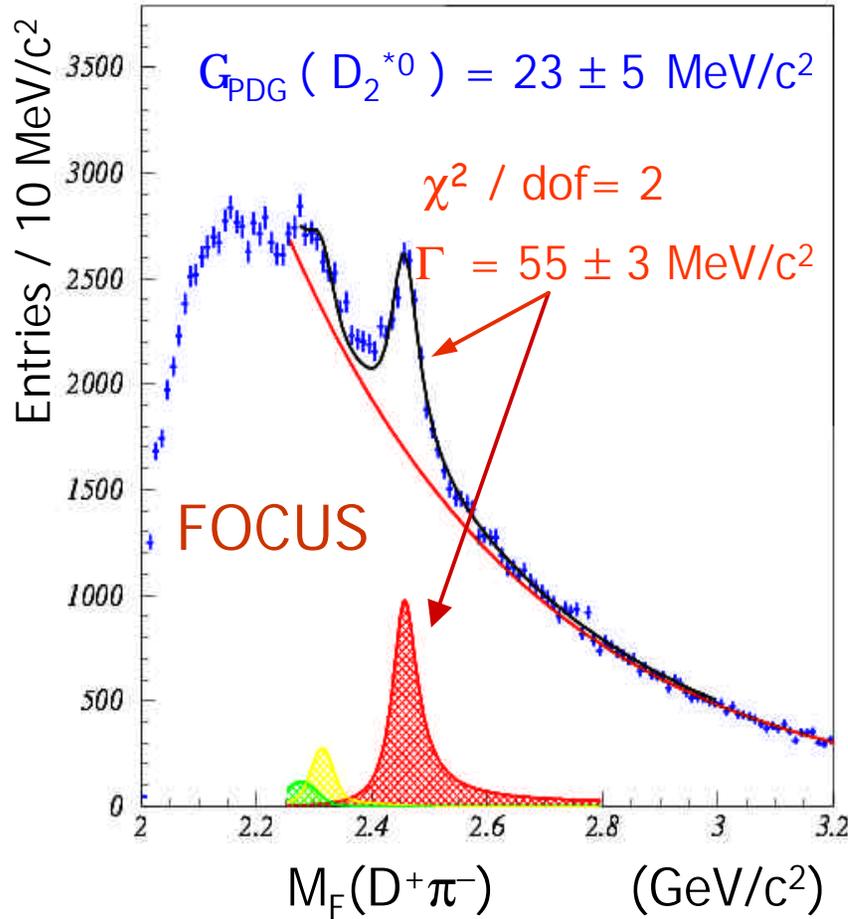


$p_\pi > 10 \text{ GeV}/c$   
➔

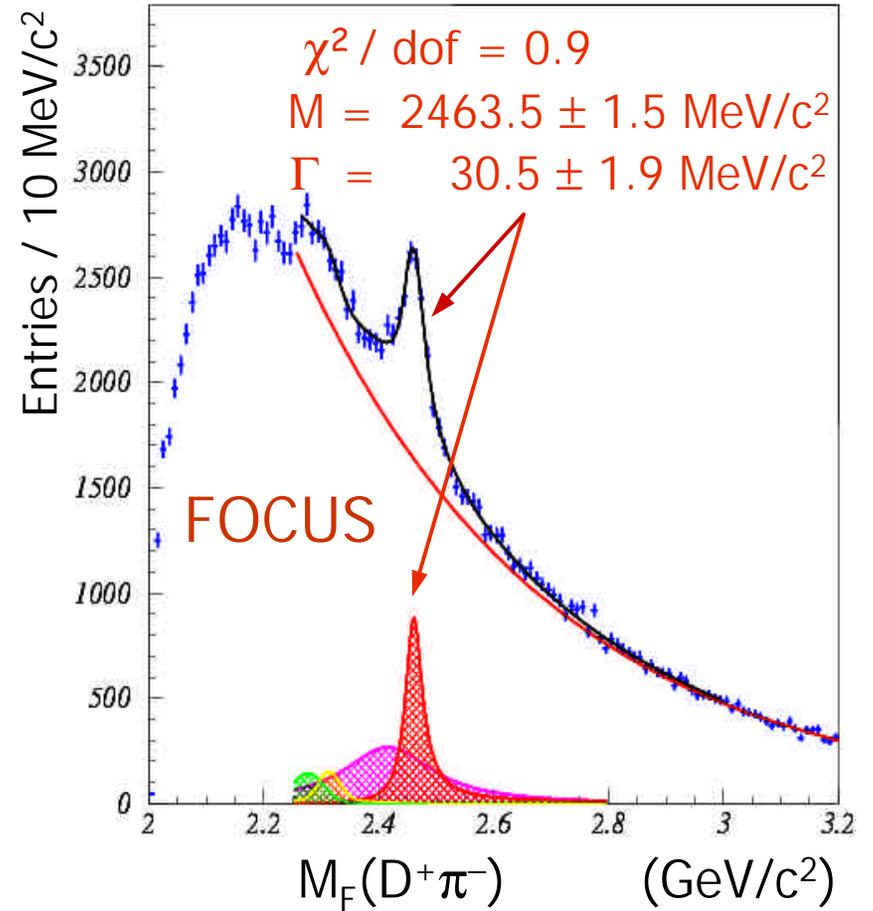
Pion momentum (GeV/c)



# Fitting the $D^+\pi^-$ Mass Distribution

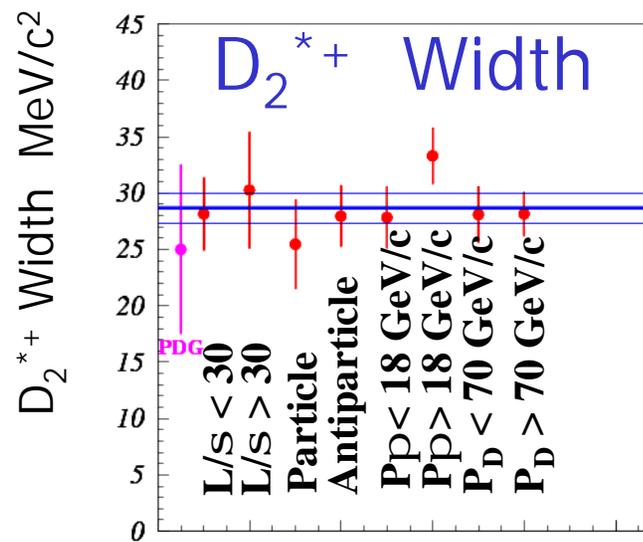
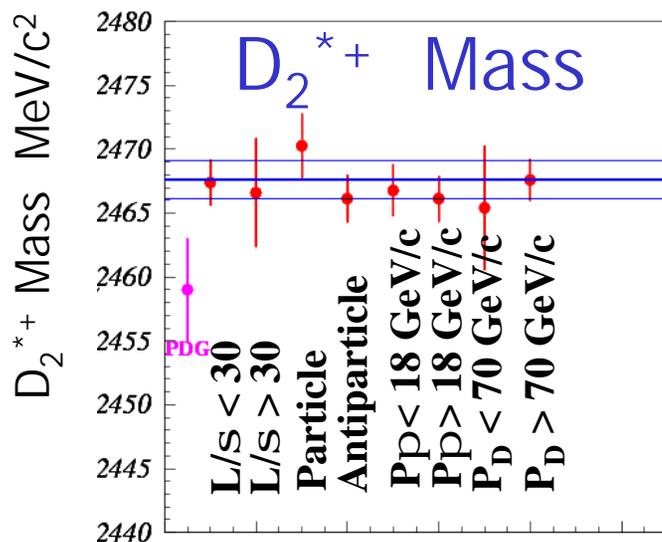


Signal + Exp +  $D_1$  +  $D_2$



+ S-Wave Rel. BW

# $D_2^*$ Mass and Width Systematics



Preliminary

## FOCUS $D_2^*$ Results

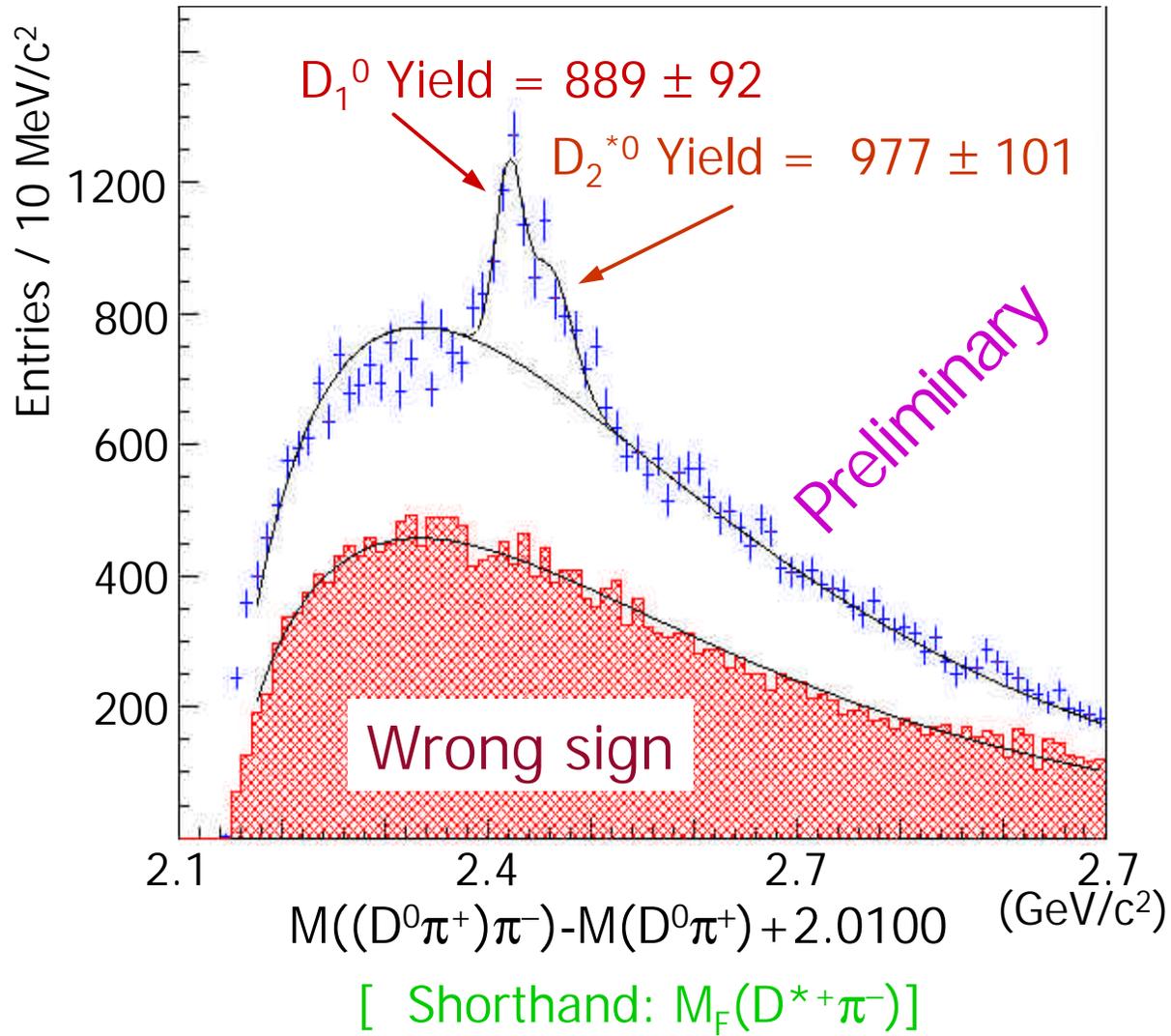
Mass ( $\text{MeV}/c^2$ )

$\Gamma$  ( $\text{MeV}/c^2$ )

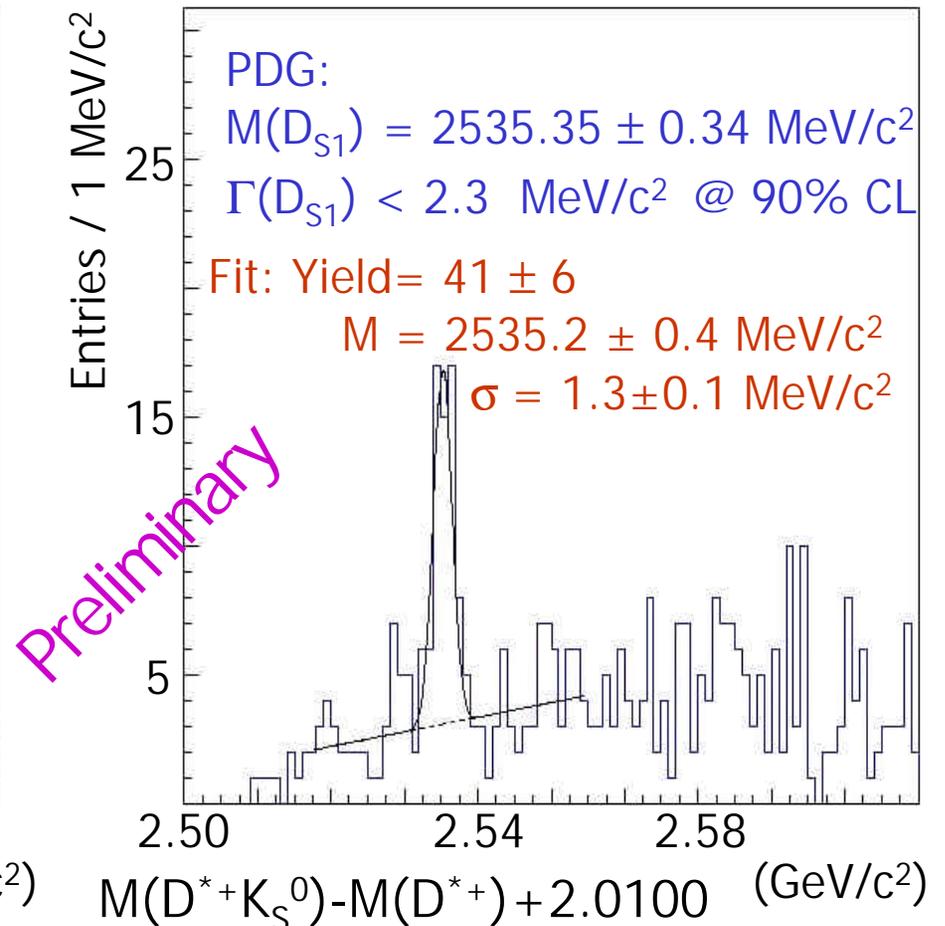
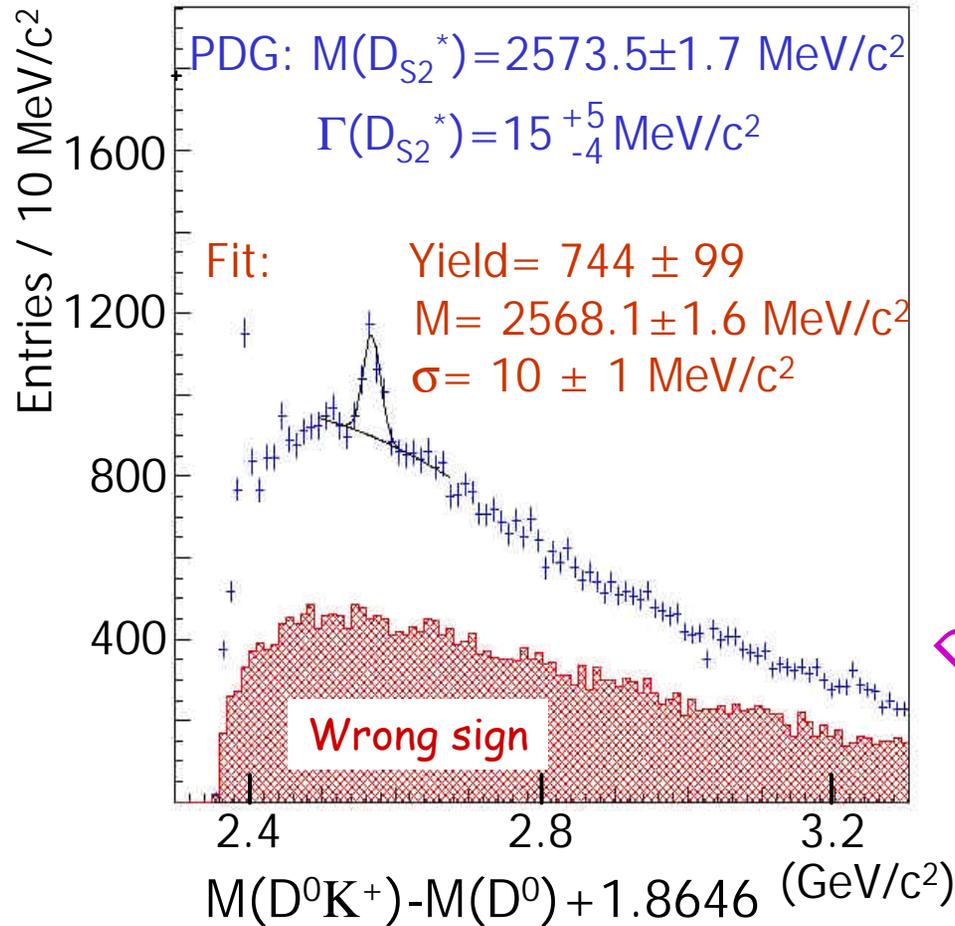
$D_2^{*+}$	$2468.2 \pm 1.5 \pm 1.4$	$28.6 \pm 1.3 \pm 3.8$
$D_2^{*0}$	$2463.5 \pm 1.5 \pm 1.5$	$30.5 \pm 1.9 \pm 3.8$

PDG 2000:  $M^+ = 2459 \pm 4$ ,  $M^0 = 2458.9 \pm 2.0$ ,  $\Gamma^+ = 25 \pm 8$ ,  $\Gamma^0 = 23 \pm 5 \text{ MeV}/c^2$ .

# $D^{*+}\pi^-$ Mass Distribution



# Excited $c\bar{s}$ Mesons at FOCUS



Stat errors only.  $D_{S_1}$  width consistent with detector resolution.

# Summary and Conclusions

- Measurements of  $\Sigma_c^{++}$  and  $\Sigma_c^0$  Masses and Widths
  - Published:  $M(\Sigma_c^{++}) - M(\Sigma_c^0) = -0.03 \pm 0.28 \pm 0.11 \text{ MeV}/c^2$
- Confirm  $\Sigma_c^+$ ,  $\Sigma_c^{*++}$ ,  $\Sigma_c^{*0}$  previously seen only by CLEO II.
- Preliminary masses and widths for the narrow  $D^{**}$  states:

	Mass (MeV/c <sup>2</sup> )	$\Gamma$ (MeV/c <sup>2</sup> )
$D_2^{*+}$	$2468.2 \pm 1.5 \pm 1.4$	$28.6 \pm 1.3 \pm 3.8$
$D_2^{*0}$	$2463.5 \pm 1.5 \pm 1.5$	$30.5 \pm 1.9 \pm 3.8$

- Now confronting a new level of systematics in the  $D^{**}$  sector.
  - We need something resembling the expected broad states in order to fit the mass spectrum successfully.
- A good start on  $\Lambda_c^*$  and  $D_s^{**}$  states.

## References for Theory on Page 13

1. M.A. Ivanov et al., Phys. Lett. B442, 435 (1998).
2. M.A. Ivanov et al., Phys. Rev. D60, 094002 (1999).
3. S. Tawfig et al., Phys. Rev. D58, 054010 (1998).
4. M.-Q. Huang et al., Phys. Rev. D52, 3986 (1995).
5. D. Pirol and T.-M. Yan, Phys. Rev D56, 5483 (1997).
6. J.L. Rosner, Phys. Rev. D52, 6461 (1995).